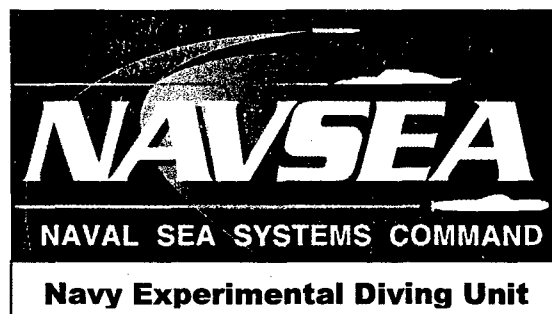


Navy Experimental Diving Unit  
321 Bullfinch Rd.  
Panama City, FL 32407-7015

TA 04-16  
NEDU TR #05-02  
07 Mar 2005

# **MANNED EVALUATION OF A PROTOTYPE COMPOSITE COLD WATER DIVING GARMENT USING LIQUIDS AND SUPERINSULATION AEROGEL MATERIALS**



20060213 106

Authors: M. L. Nuckols, Ph.D.  
J. C. Chao, M.D.  
M. J. Swiergosz, Ph.D.

DISTRIBUTION STATEMENT A.  
Approved for public release;  
distribution is unlimited.

UNCLASSIFIED  
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE					
1a. REPORT SECURITY CLASSIFICATION Unclassified		1b. RESTRICTIVE MARKINGS			
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.			
2b. DECLASSIFICATION/DOWNGRADING AUTHORITY					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NEDU Technical Report No.05-02		5. MONITORING ORGANIZATION REPORT NUMBER(S)			
6a. NAME OF PERFORMING ORGANIZATION Navy Experimental Diving Unit	6b. OFFICE SYMBOL (If Applicable) 02	7a. NAME OF MONITORING ORGANIZATION			
6c. ADDRESS (City, State, and ZIP Code) 321 Bullfinch Road, Panama City, FL 32407-7015		7b. ADDRESS (City, State, and Zip Code)			
8a. NAME OF FUNDING SPONSORING ORGANIZATION Naval Sea Systems Command	8b. OFFICE SYMBOL (If Applicable) 00C3	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER			
8c. ADDRESS (City, State, and ZIP Code)  2531 Jefferson Davis Highway, Arlington, VA 22242-5160		10. SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO. 04-16	
11. TITLE (Include Security Classification) (U) MANNED EVALUATION OF A PROTOTYPE COMPOSITE COLD WATER DIVING GARMENT USING LIQUIDS AND SUPERINSULATION AEROGEL MATERIALS					
12. PERSONAL AUTHOR(S) M. L. NUCKOLS, J. C. CHAO, M. J. SWIERGOSZ					
13a. TYPE OF REPORT Technical Report	13b. TIME COVERED 2005 JAN 10-14	14. DATE OF REPORT (Year, Month, Day) 2005 MAR 1	15. PAGE COUNT 24		
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)  Aerogel, Cold Water Composite Diving Garment, Superinsulation Materials			
FIELD	GROUP				SUB-GROUP
19. ABSTRACT The objective of this study was to quantify physical and psychological characteristics in divers wearing recently developed materials designed to enhance thermal protection in cold water. A repeated measures series consisting of twelve total man dives was conducted in 35 to 40 °F water up to six hours in duration, a series in which both the diver's physiological and thermal conditions were measured as a function of thermal garments (aerogel and Thinsulate) worn under commercial dry suits. Mean dive duration increased significantly when diver-subjects wore the prototype aerogel garment (126.2 min): on average, 38% longer than dives with the Thinsulate liners (91.2 min). The aerogel prototype garment also significantly improved thermal protection of the fingers and toes, body regions where thermal stress had been a primary reason for aborting dives. In-water and postdive surveys confirmed the overall thermal benefits of the prototype aerogel liner.					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT  <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION  Unclassified			
22a. NAME OF RESPONSIBLE INDIVIDUAL NEDU Librarian	22b. TELEPHONE (Include Area Code) 850-230-3100	22c. OFFICE SYMBOL			

DD Form 1473

UNCLASSIFIED  
SECURITY CLASSIFICATION OF THIS PAGE

**PAGE INTENTIONALLY LEFT BLANK**

## **ACKNOWLEDGMENTS**

This research was made possible through funding from the Office of Naval Research (ONR), Ocean Engineering and Marine Systems Science and Technology Program, ONR Code 321OE.

**PAGE INTENTIONALLY LEFT BLANK**

## CONTENTS

	<u>Page No.</u>
DD Form 1473 .....	i
Acknowledgments .....	ii
Contents .....	iii
Figures and Tables .....	iv
Introduction .....	1
Methods .....	2
General .....	2
Diver-Subjects .....	3
Diver Dress and Breathing Apparatus .....	4
Instrumentation .....	4
Procedures .....	6
Termination Criteria .....	6
Results .....	7
General .....	7
Dive Duration .....	7
Finger, Toe, and Core Temperatures .....	8
Depth, Time, and Temperature Records .....	10
Global Skin Temperatures .....	10
Localized Skin Temperatures .....	11
In-Water Questionnaire .....	13
Postdive Questionnaire .....	14
Discussion .....	14
Conclusions / Recommendations .....	15
References .....	16
Appendix A. In-Water Thermal Assessment Questionnaire .....	A-1
Appendix B. In-Water Thermal Assessment Questionnaire Data .....	B-1
Appendix C. Postdive Questionnaire .....	C-1

**PAGE INTENTIONALLY LEFT BLANK**

## FIGURES

Figure 1A.	Aspen aerogel cloth superinsulation .....	1
Figure 1B.	Aspen aerogel cloth superinsulation (detail) .....	1
Figure 2.	Layers of diver dress.....	5
Figure 3.	Diver preparing to enter the test pool.....	5
Figure 4.	Mean dive duration (min) as a function of the thermal garment.....	8
Figure 5.	Mean finger temperature (°C) drop from the baseline as a function of the thermal garment. ....	9
Figure 6.	Mean toe temperature (°C) drop from the baseline as a function of the thermal garment .....	9
Figure 7.	Mean skin temperature (°C) drop from the baseline as a function of the thermal garment .....	10
Figure 8.	Mean chest skin temperature (°C) drop from the baseline as a function of the thermal garment.....	12
Figure 9.	Mean thigh skin temperature (°C) drop from the baseline as a function of the thermal garment.....	12
Figure 10.	Mean calf skin temperature (°C) drop from the baseline as a function of the thermal garment .....	13
Figure 11.	Mean upper arm skin temperature (°C) drop from the baseline as a function of the thermal garment .....	13

## TABLES

Table 1.	Age, Weight, and Body Fat Characteristics of Diver-Subjects .....	3
Table 2.	Dive Durations and Abort Criteria in Relation to Thermal Garment Performance. ....	7
Table 3.	Mean Finger, Toe, and Core Temperature (°C) Changes from Baseline as a Function of Thermal Garment Performance. ....	8
Table 4.	Mean DTTR Skin Temperature (°C) Drops from Baseline as a Function of Thermal Garment Performance.....	10
Table 5.	Localized Mean DTTR Skin Temperature (°C) Drops from Baseline as a Function of Thermal Garment Performance. ....	11



**PAGE INTENTIONALLY LEFT BLANK**

## INTRODUCTION

Naval Sea Systems Command (NAVSEA) 00C tasked Navy Experimental Diving Unit (NEDU) to assess the effectiveness of an experimental composite cold water diving garment developed in a partnership among Southwest Research Institute (San Antonio, TX), Duke University (Durham, NC), and Aspen Systems (Marlborough, MA) under the sponsorship of the Office of Naval Research (ONR).<sup>1</sup> The objective of this assessment was to quantify physical and psychological characteristics of divers wearing materials recently developed to enhance thermal protection in cold water. This proof of concept study was designed to determine whether incorporating a composite liner in a thermal undergarment containing superinsulation aerogel materials inside commercial dry suits could significantly enhance the divers' thermal performances.

In 1996, cold water investigations at the Naval Medical Research Institute (NMRI; Bethesda, MD) demonstrated the inadequacy of existing diver thermal protection for combat swimmers in long-duration cold water missions. To address this deficiency by supplementing the insulation of divers' dry suits, a suit liner system containing superinsulating aerogel materials is being developed under the sponsorship of ONR.<sup>2</sup> Originally funded by the National Aeronautics and Space Administration (NASA) to develop next generation spacesuit insulation for extravehicular activity on Mars, flexible aerogel composites suitable for submerged conditions are also being developed. Aspen Systems has developed a flexible aerogel composite insulation with a thermal performance equal to that of the best solid insulation (brittle monolithic aerogels) known and yet with a much more practical form (Figures 1A and 1B).

The new insulation comes in a thin blanket form amenable to cutting and shaping techniques common to the clothing industry. The blankets have a measured thermal conductivity of 10–14 mW/m-K (R-value of 14–10 per inch) in ambient conditions, a specific gravity of around 0.1, an excellent flexibility without loss of thermal performance over many tens of thousands of bending cycles, and a superior acoustical absorption capability compared to that of conventional rubber insulation used in diving suits.



**Figure 1A.** Aspen aerogel cloth superinsulation draped over a human arm.



**Figure 1B.** Close-up of the Aspen aerogel cloth superinsulation.

Southwest Research Institute contracted Diving Unlimited International (DUI), Inc., to fabricate prototype aerogel garments consisting of Aspen Aerogel AR5401 panels encapsulated with Pertex nylon oxford covering in medium, large, and extra large sizes. Except for using a single ply of AR5401 in the arms, the prototype construction was a one-piece coverall with two ply of these panels. Booties were also fabricated with two ply of AR5401 and Velcro straps to secure ankle closures; three-finger glove liners and a skull cap were fabricated from a single ply of AR5401. The large-size coverall weighed 2.26 kg (4.98 lb) and had a thickness of 0.248 inches for the two-ply regions and 0.154 inches for the single-ply regions. Before testing began, Patagonia lightweight underwear, crew shirt, and pants were positioned beneath the aerogel undergarment, and the entire ensemble was outfitted with a DUI TLS350 trilaminate dry suit and three-finger dry glove shells (Figures 2 and 3). Along with M400 Thinsulate<sup>\*</sup> booties and three-finger polyurethane glove liners, a commercial M400 Thinsulate coverall undergarment weighing 2.06 kg (4.54 lb; Figure 2A), was used as the baseline garment for comparing thermal performance. This garment was tested with the same Patagonia thermal underwear and DUI Trilaminate dry suit ensemble.

Preliminary analyses later confirmed by manikin testing at the Naval Clothing and Textile Research Facility in Natick, MA, indicated that the prototype liner had an inherent thermal insulation value 67% greater than that of the M400 Thinsulate ensemble: 1.99 CLO<sup>†</sup> for the prototype aerogel garment, compared to 1.18 CLO for the Thinsulate baseline garment.

## METHODS

### GENERAL

During January 2005, NEDU conducted a repeated measures series of twelve test dives up to six hours in duration to compare the thermal performance of the prototype aerogel garment with the baseline Thinsulate worn under a commercial dry suit. The thermal benefit of the experimental aerogel garment was determined by statistics describing psychological and physical thermal status data from the aerogel and the commercial Thinsulate garments. All tests were conducted to simulate long-duration cold water conditions in the NEDU test pool, where water temperature was maintained between 1.7 and 4.4 °C (35 and 40 °F). Divers remained immobile while either lying or sitting in chairs on the bottom of the test pool, and they subjectively reported their thermal comfort at 30-minute intervals during each dive.

---

<sup>\*</sup> Thinsulate is a registered trademark of 3M Corporation.

<sup>†</sup> CLO is a unit of thermal protection that is characterized as the amount of insulation inherent in a business suit when worn in air. It can be quantified as 1.136 divided by the suit conductance, where suit conductance is measured in Btu/ft<sup>2</sup>-hr-°F.

## DIVER-SUBJECTS

Six U.S. Navy male divers — whose age, weight, and body fat statistics are listed in Table 1 — volunteered to participate in the study. Skinfold measurements from three locations (chest, abdomen, and thigh) were used to estimate the percent body fat for each diver-subject. Body density was calculated with the generalized equation from Jackson and Pollock,<sup>3</sup>

$$\text{Body Density} = 1.10938 - 0.0008267 * \text{sum} + 0.0000016 * \text{sum}^2 - 0.0002574 * \text{age},$$

and the Siri equation<sup>4</sup> was used to estimate the percentage of body fat. These equations provide estimates for white males between the ages of 20 and 80.

Body fat percentage (%Fat) was then estimated from body density by using the expression

$$\% \text{Fat} = \left[ \frac{4.570}{\text{Body Density}} - 4.142 \right] * 100\%.$$

To ensure that their baseline core temperatures would not be elevated before their dives, diver-subjects did not conduct physical training (PT) on dive days.

The protocol<sup>5</sup> was reviewed and approved by the NEDU Institutional Review Board (IRB). All test subjects reviewed the protocol and voluntarily consented to participate in the study.

**Table 1.** Age, Weight, and Body Fat Characteristics of Diver-Subjects.

Diver ID	Age	Weight (kg)	Weight (lb)	Body fat%
1	35	88.0	194.0	16.8
2	40	85.3	188.0	11.2
3	30	88.4	195.0	11.0
4	36	92.5	204.0	18.5
5	49	91.8	202.5	16.9
6	40	80.7	178.0	12.9
Mean	38.3	87.8	193.6	14.6
Std Dev	6.4	4.4	9.6	3.2
Min	30	80.7	178.0	11.0
Max	49	92.5	204.0	18.5

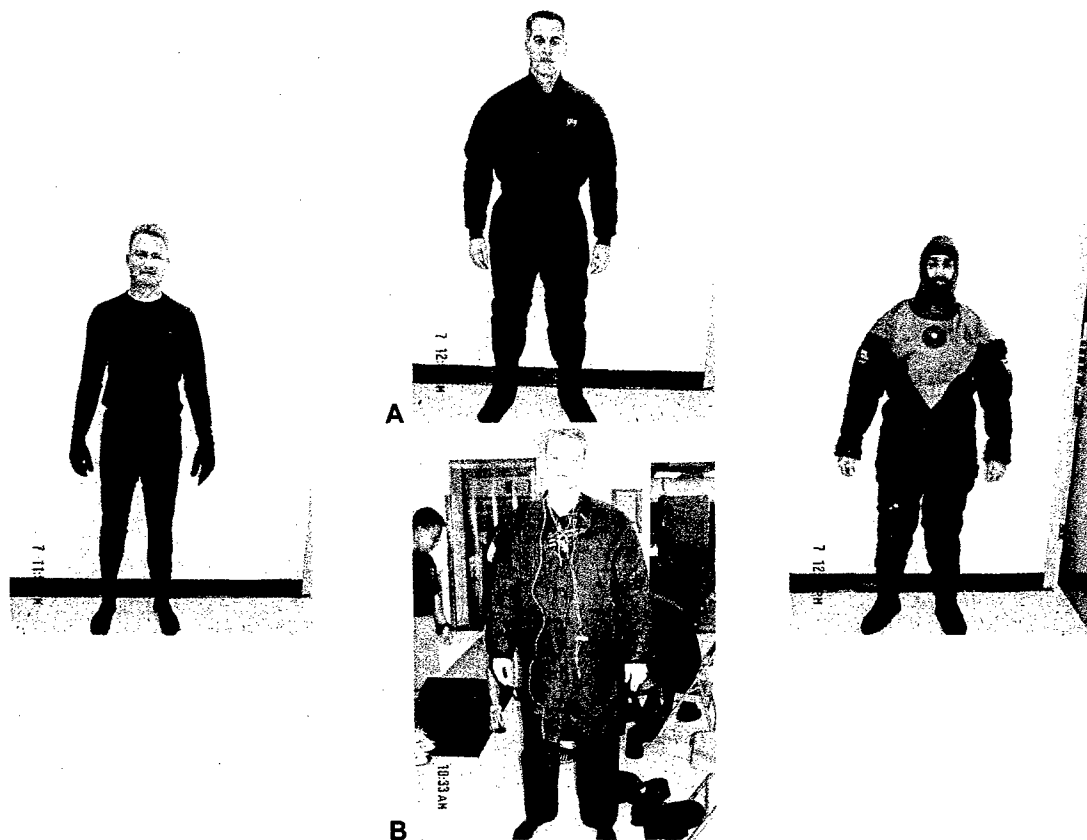
## **DIVER DRESS AND BREATHING APPARATUS**

For hygiene purposes, diver-subjects wore external catheter urine collection systems during the dive. Diver dress (Figure 2) consisted of three layers. The first layer was Capilene lightweight underwear, socks, and gloves. The second layer was one of the two suit configurations tested: the M400 Thinsulate thermal liner (Figure 2A), or the prototype aerogel thermal liner (Figure 2B). The third layer was a commercial DUI TLS350 dry suit with an attached hood, and all divers wore three-finger dry gloves.

Diver-subjects used the U.S. Navy MK 20 underwater breathing apparatus (UBA) with built-in communications. A complete diver dress and breathing apparatus configuration is shown in Figure 3.

## **INSTRUMENTATION**

Rectal ( $T_{\text{rec}}$ ), finger ( $T_{\text{finger}}$ ), and toe ( $T_{\text{toe}}$ ) temperatures were monitored in real time with a YSI series 700 thermistor (Yellow Springs Instruments Inc; Yellow Springs, OH) as an indicator of core and surface temperatures and also as a monitor of physiological safety. Depth, time, and temperature recorders (DTTR; PAG Automasjon A/S, Mo i Rana, Norway) were used to record chest, thigh, calf, and upper arm skin temperatures for postdive thermal assessment of these areas. Their sampling rates and data storage capacities were adequate for recording skin temperature changes through a six-hour dive.



**Figure 2.** Layers of diver-dress from left to right: the Capilene lightweight underwear, socks, and gloves; (A) the M400 Thinsulate thermal undergarment, or (B) the prototype aerogel liner (booties, gloves, and skullcap not shown); and the TLS350 dry suit with an attached hood (three-finger dry gloves not shown). A DTTR worn around the neck is shown in (B).



**Figure 3.** Diver wearing the TLS350 dry suit with three-finger, "lobster claw" gloves as he prepares to enter the test pool.

## PROCEDURES

Baseline core temperatures were recorded immediately before diver dress was initiated. The six diver-subjects made one dive with each dry suit configuration. The order in which these dives were conducted was counterbalanced so that three of the diver-subjects wore the aerogel garment on the first dive and the Thinsulate garment on the second. This order was reversed for the three other diver-subjects. To control carryover thermal debt after their first dives, however, no diver could initiate a second dive for at least 40 hours. Core, toe, and finger temperature signals were verified before the diver-subjects entered the water. After the Dive Supervisor cleared diver-subjects, dive time was initiated as each diver entered the water and traveled to the bottom of the test pool in pairs. Each diver positioned himself in a seated or lying position to simulate a long-duration transit by SEAL delivery vehicle (SDV). Core, toe, and finger temperatures were logged at the start of the dive and every minute thereafter until the divers exited the water. Diver-subjects were continually monitored for the duration of the dive (six hours) or until termination criteria were met. A standby diver was available at all times while diver-subjects were in the water, and a hot tub and warm fluids were available to them after diving.

To subjectively assess diver thermal status, a thermal assessment questionnaire (Appendix A) was administered to the divers via the MK 20 communication system approximately every thirty minutes throughout dives. Results from diver thermal assessment questionnaires are summarized in Appendix B. A postdive questionnaire (Appendix C) was used to collect general usability data.

## TERMINATION CRITERIA

The tests were terminated before the six-hour duration if any of the following events occurred:

- A diver's core temperature dropped  $\geq 1.5$  °C (2.7 °F) below his baseline for at least five minutes or  $\leq 35.0$  °C (95.0 °F) at any time.
- A toe or finger temperature diminished  $\leq 12.0$  °C (53.6 °F) for at least five minutes or  $\leq 10.0$  °C (50.0 °F) at any time.
- A diver requested that a test be terminated.
- A dive watch officer, diving supervisor, diving medical officer, or diving corpsman determined that a dive was unsafe to continue.
- The Principal Investigator determined that termination was appropriate.
- If a single skin temperature sensor failed, diver comfort determined whether a test was terminated. (The frequency with which the in-water questionnaire was administered was increased to every 15 minutes for that diver.)

## RESULTS

### GENERAL

The results are reported in five subsections: dive duration; real-time finger, toe, and core temperature data; DTTR data; subjective questionnaire data; and postdive interviews. Comparisons between the thermal garments were conducted at 30-minute intervals to parallel the administration of in-water questionnaires. The number of comparisons was determined by the shortest dive in the group so that all diver temperatures could be assessed at each questionnaire interval. The alpha level was set at .05 for all inferential tests.

### DIVE DURATION

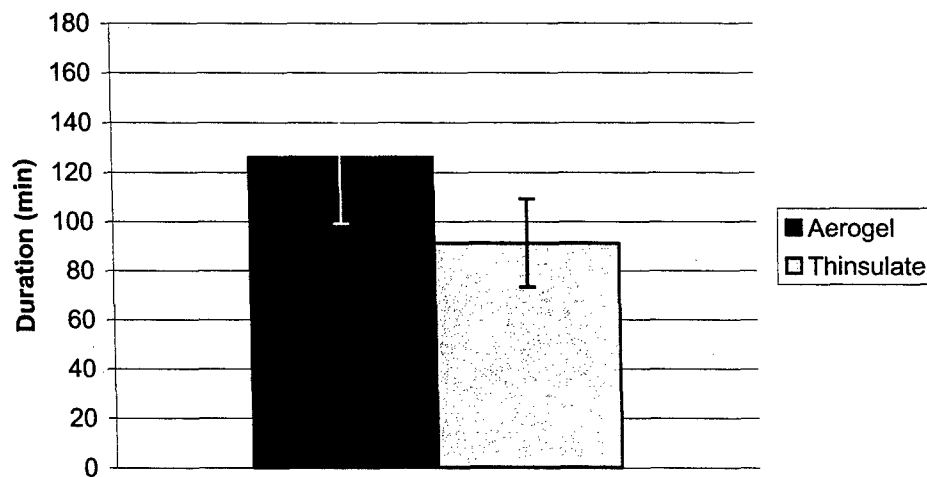
A summary of dive durations and abort criteria are provided in Table 2. As anticipated, the majority of dives (10/12) were aborted because of physical or reported thermal stress in the extremities (fingers, toes, hands, feet). No dives were aborted because of medical considerations. Figure 4 illustrates the difference in dive duration as a function of thermal garment performance. When the diver was wearing the prototype aerogel garment, dive durations were longer than they were when the diver was wearing Thinsulate:  $t(5) = 6.79$ ,  $p < .05$ .

**Table 2.** Dive Durations and Abort Criteria in Relation to Thermal Garment.

Diver ID	Dive Duration (min)		Abort Criterion	
	Aerogel	Thinsulate	Aerogel	Thinsulate
1	157	113	finger	voluntary <sup>4</sup>
2	96	63	finger	finger
3	101	81	finger <sup>1</sup>	toe
4	109	88	toe	finger
5	147	106	voluntary <sup>2</sup>	finger/toe
6	147	96	voluntary <sup>3</sup>	finger/toe
Mean	126.2	91.2		
Std Dev	27.0	18.0		

**Notes:** Mean dive durations are reported in minutes with one standard deviation. Unless otherwise noted, the reason for abort was due to thermal stress in the indicated area. <sup>1</sup>The right arm flooded — hand was dry. <sup>2</sup>Discomfort caused by hood pressure on the diver's jaw. <sup>3</sup>Diver had to urinate, refused to wear catheter. <sup>4</sup>Diver reported cold hands and feet.





**Figure 4.** Mean dive duration (min) as a function of thermal garment. Error bars represent one standard deviation.

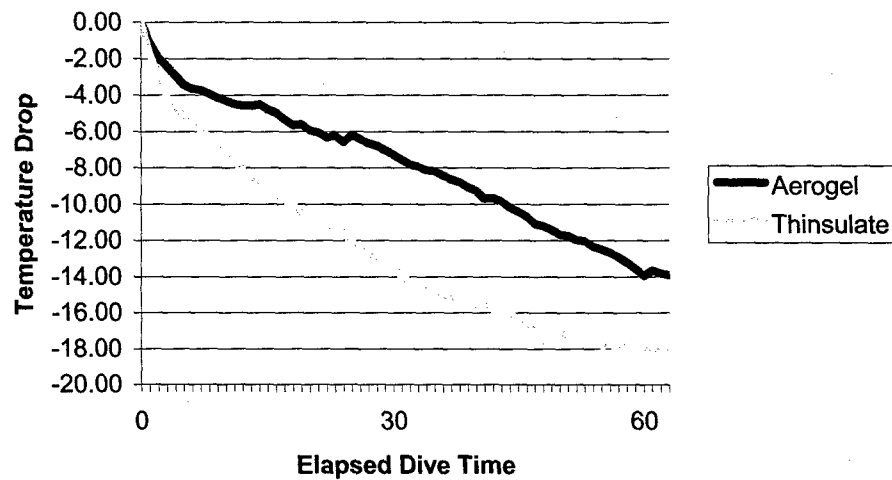
## FINGER, TOE, AND CORE TEMPERATURES

Table 2 indicates that the shortest recorded dive (Diver 2, Thinsulate) was 63 minutes. For all divers, temperature drops from baselines were thus calculated up to the 63-minute mark of each dive in order to assess differences in thermal protection. Finger, toe, and core temperature changes from baselines at the 30- and 60-minute dive intervals are presented in Table 3. Figures 5 and 6 illustrate finger and toe temperature drops from baseline as a function of thermal garment.

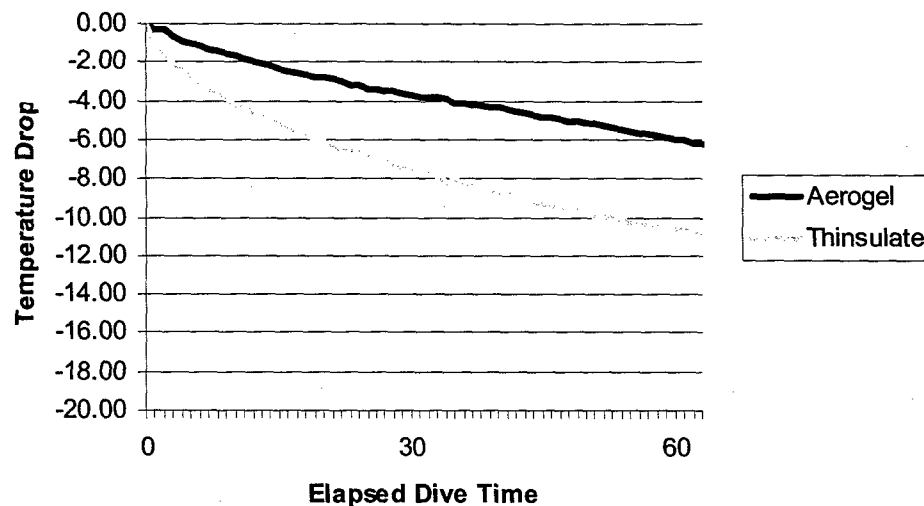
**Table 3.** Mean Finger, Toe, and Core Temperature (°C) Changes from Baseline as a Function of Thermal Garment.

	30 Minutes		60 Minutes	
	Aerogel	Thinsulate	Aerogel	Thinsulate
<b>Finger</b>	-7.29 (4.86)	-13.59 (1.53)	-13.96 (3.34)	-18.18 (1.74)
<b>Toe</b>	-3.31 (1.29)	-7.00 (1.27)	-5.97 (1.60)	-10.63 (1.67)
<b>Core</b>	0.50 (0.30)	0.47 (0.30)	0.28 (0.28)	0.17 (0.39)

**Note:** Mean temperature changes (top) are reported with one standard deviation (below). One toe temperature in the aerogel condition was lost at the 30-minute dive interval; the next available score (26-minute mark) was used for both garment conditions.



**Figure 5.** Mean finger temperature (°C) drop from baseline as a function of thermal garment. Data are shown up to the shortest (63 min) recorded dive.



**Figure 6.** Mean toe temperature (°C) drop from baseline as a function of thermal garment. Data are shown up to the shortest (63 min) recorded dive.

Temperature drops in the fingers and toes at the 30-minute dive interval were attenuated more when divers were wearing the prototype aerogel garment than when they were wearing Thinsulate:  $t(5) = 3.14$ ,  $p < .05$  (finger), and  $t(5) = 3.84$ ,  $p < .05$  (toe). This pattern of thermal protection was also evident at the 60-minute interval for the toes —  $t(5) = 3.79$ ,  $p < .05$  — and was marginally significant for the finger:  $t(5) = 2.20$ ,  $p = .079$ . Core temperature did not vary as a function of protective garment.

## DEPTH, TIME, AND TEMPERATURE RECORDINGS

### Global Skin Temperature

Because of the difficulty in measuring many anatomical sites, the mean skin temperature developed by Ramanathan<sup>6</sup> was used to calculate the mean body temperature and heat storage for measurements of depth, time, and temperature. The mean skin temperature values were based on regional weighting according to the percentage of body surface area. The formula for mean skin temperature ( $T_{sk}$ ) is

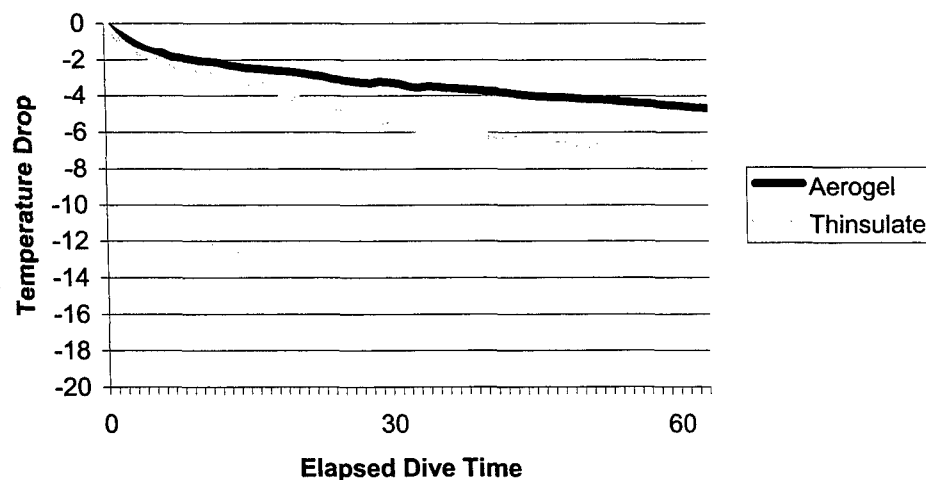
$$T_{sk} = 0.3 \cdot (\text{chest} + \text{upper arm temperatures}) + 0.2 \cdot (\text{thigh} + \text{calf temperatures}).$$

Mean skin temperature drops from baseline at the 30- and 60-minute intervals are presented in Table 4 and illustrated in Figure 7. An excessive amount of DTTR data was lost for Diver #4; thus, he was excluded from these calculations.

**Table 4.** Mean DTTR Skin Temperature (°C) Drops from Baseline as a Function of Thermal Garment.

	30 Minutes		60 Minutes	
	Aerogel	Thinsulate	Aerogel	Thinsulate
Mean	-3.22	-5.25	-4.52	-7.15
Std Dev	1.57	2.07	2.13	1.79

Note: Diver #4 is excluded from the calculations since most of his DTTR data was lost near the 30- and 60-minute intervals. It was later discovered that the DTTR for Diver #4 had a faulty sensor. The sensor was replaced and the DTTR unit was returned to service.



**Figure 7.** Mean skin temperature (°C) drop from baseline as a function of thermal garment. Data is shown up to the shortest (63 min) recorded dive.

As a function of thermal garment, the drop in mean skin temperature approached but did not attain statistical significance at the 30- and 60-minute dive intervals:  $t(4) = 1.86$ ,  $p = .137$ ; and  $t(4) = 2.30$ ,  $p = .083$ , respectively.

### *Localized Skin Temperatures*

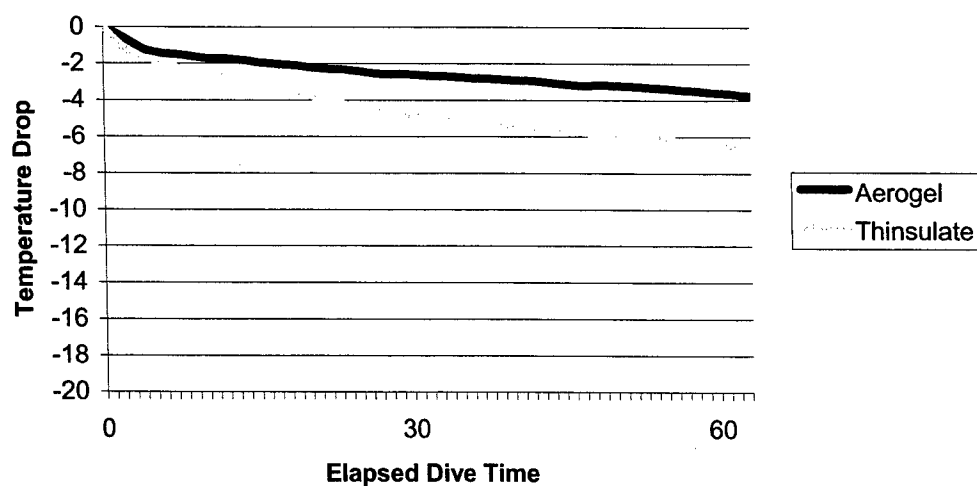
For chest, thigh, calf, and upper arm at the 30- and 60-minute dive intervals, mean skin temperature drops from baseline are presented in Table 5. Figures 8–11 illustrate these skin temperature drops from baseline as a function of thermal garment.

**Table 5.** Localized Mean DTTR Skin Temperature (°C) Drops from Baseline as a Function of Thermal Garment.

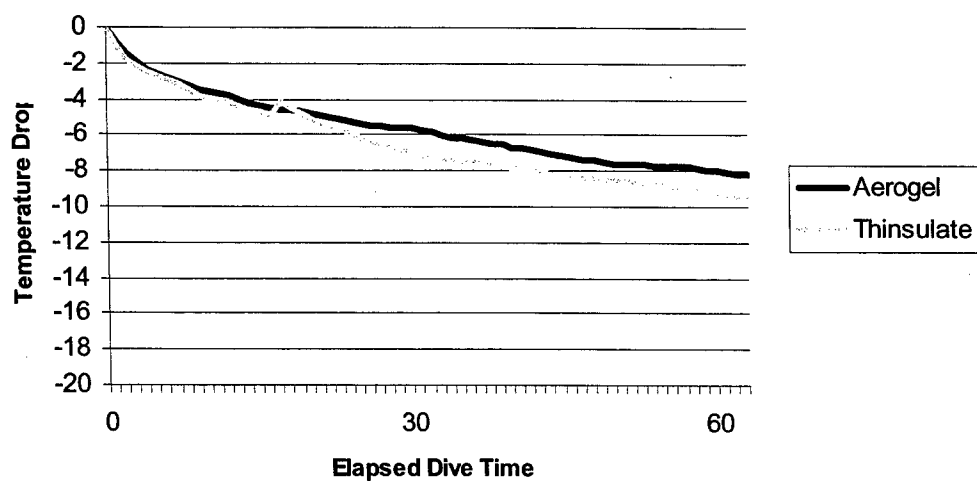
	30 Minutes		60 Minutes	
	Aerogel	Thinsulate	Aerogel	Thinsulate
<b>Chest</b>	-2.59 (1.59)	-4.86 (2.89)	-3.57 (2.28)	-6.54 (3.24)
<b>Thigh</b>	-5.60 (3.85)	-6.99 (2.65)	-7.93 (4.45)	-9.33 (2.21)
<b>Calf</b>	-1.90 (0.71)	-7.12 (1.70)	-3.10 (1.02)	-9.94 (1.02)
<b>Upper Arm</b>	-3.50 (1.80)	-3.91 (1.91)	-4.68 (2.15)	-5.13 (1.97)

Note: Mean temperature drops (top) are reported with one standard deviation (below). Diver #4 was excluded from calf calculations, since DTTR data were lost at this location.

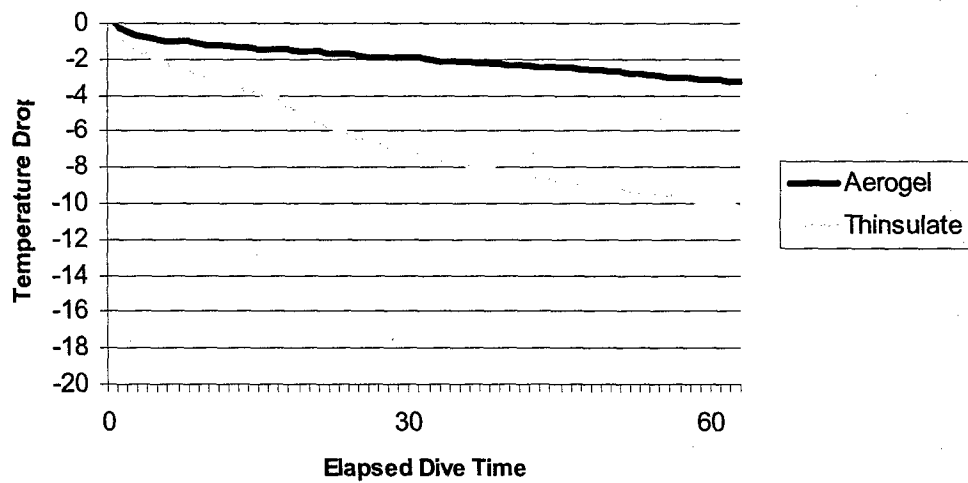
Chest temperature drops at the 30- and 60-minute dive intervals were attenuated more when divers were wearing the prototype aerogel garment than when they were wearing Thinsulate:  $t(5) = 3.15$ ,  $p < .05$  (30 minutes); and  $t(5) = 2.65$ ,  $p < .05$  (60 minutes). Calf temperature drops at the 30- and 60-minute marks were also attenuated more when divers were wearing the prototype aerogel garment than when they were wearing Thinsulate:  $t(4) = 12.94$ ,  $p < .05$  (30 minutes); and  $t(4) = 19.14$ ,  $p < .05$  (60 minutes). Thigh and upper arm temperatures at the 30- and 60-minute dive intervals did not vary as a function of protective garment.



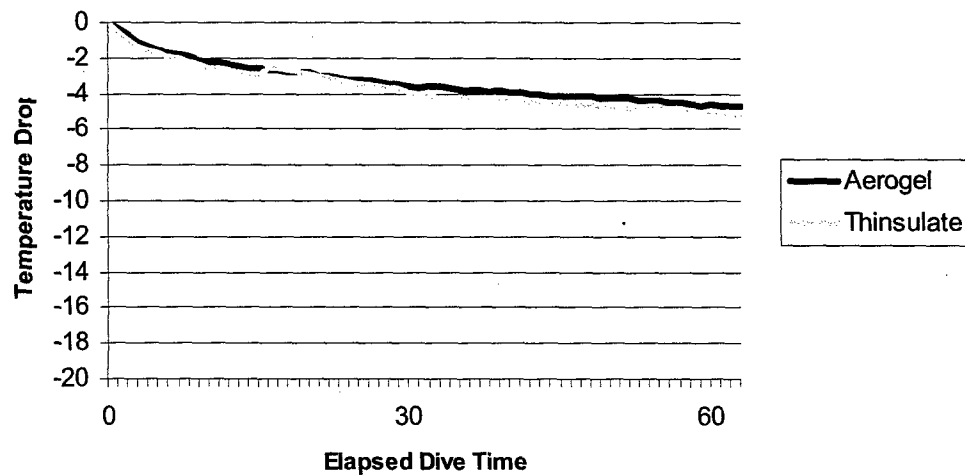
**Figure 8.** Mean chest skin temperature (°C) drop from baseline as a function of thermal garment. Data is shown up to the shortest (63 min) recorded dive.



**Figure 9.** Mean thigh skin temperature (°C) drop from baseline as a function of thermal garment. Data is shown up to the shortest (63 min) recorded dive.



**Figure 10.** Mean calf skin temperature (°C) drop from baseline as a function of thermal garment. Data is shown up to the shortest (63 min) recorded dive.



**Figure 11.** Mean upper arm skin temperature (°C) drop from baseline as a function of thermal garment. Data is shown up to the shortest (63 min) recorded dive.

## IN-WATER QUESTIONNAIRE

Responses to thermal status questions 3–6 (Appendix A) at the 30-minute dive interval are not related to dive duration. However, numerical responses to Question 4 (“Are your hands cold or hot?”) at the 60-minute dive interval are significantly related to dive duration:  $r = .49$ ,  $p < .05$ . The relationship between dive duration and responses to Question 5 (“Are your feet cold or hot?”) was relatively strong at the 60-minute dive interval ( $r = .72$ ), but the probability of obtaining this correlation by chance exceeded the alpha criterion,  $p = .082$ . Responses to the question about the thermal status of the hand were related to finger temperature drops at the 30- ( $r = .69$ ,  $p < .05$ ) and 60-minute ( $r = .64$ ,  $p < .05$ ) intervals.

## POSTDIVE QUESTIONNAIRE

All the divers made comments consistent with the general finding that the prototype aerogel garment provided more thermal protection than the Thinsulate garment. All divers also reported that the three-finger glove limited their dexterity, a limitation which is not surprising because of its design. After using both thermal garments, two divers reported that their maneuverability/dexterity was superior in the Thinsulate garment. These same two divers suggested improvements be made in aerogel flexibility.

## DISCUSSION

Although the small number of test subjects reduces the statistical power of this study, several important conclusions can be drawn from the current findings. The most important is that the insulation provided by the prototype aerogel garment significantly increases dive durations. The dive duration afforded by the prototype aerogel was approximately 38% longer than that with the Thinsulate liners. This difference is impressive, since the current study probably underestimates the mean dive duration for the prototype aerogel garment: at least two of six dives were aborted for reasons unrelated to the garment's performance (see Table 2 notes).

The results confirm the futility of protecting a diver's torso, arms, and legs in cold water diving without simultaneously providing adequate thermal protection for the hands and feet. The prototype aerogel liner enhanced thermal protection of the finger ( $\sim 4^{\circ}\text{C}$ ) and toe ( $\sim 5^{\circ}\text{C}$ ), but dive aborts were predominately dictated by cold hands and feet. Responses to the in-water questionnaire also indicated enhanced thermal benefit from the prototype aerogel in these regions, and on the postdive questionnaire, divers also responded that they felt warmer in this garment.

Increased dive durations may be possible by providing additional thermal protection to the hands and feet. Such added protection will most likely mean localized active heating of the hands is necessary, since the three-finger dry gloves noticeably diminished the dexterity of the divers' hands. Increasing insulation thickness to the hands will only degrade dexterity even further.

Compared to the pre-dive baseline core temperature, the average core temperature change for diver-subjects shows a small increase ( $< 0.5^{\circ}\text{C}$ ) at both 30 and 60 minutes. Temperature rose at the start of the dive, and a gradual decline in rectal temperature followed. This result indicates that deep body cooling was not a significant factor in these dives and that diver comfort was more accurately reflected in surface skin temperatures than in core temperatures.

Although mean skin temperature drops between the two garments were not statistically significant at the tested dive intervals, mean skin temperature reductions one hour into the dive for divers wearing the prototype aerogel garment were approximately  $3^{\circ}\text{C}$  less than mean skin temperature drops for divers who wore Thinsulate.

Postdive comments revealed that the prototype aerogel garment might be less flexible than the Thinsulate garment. Two divers indicated that the prototype aerogel material hindered their maneuverability. Some of the difficulty in diver mobility may be attributed to the limited sizes of dry suits available to the divers, since some divers had to wear smaller suits than they desired. A more flexible aerogel material and improvements in sizing of patterned garments — the aerogel was particularly bulky in the lower legs — should improve diver mobility.

### **CONCLUSIONS / RECOMMENDATIONS**

1. Dive duration in cold water (35–40 °F) was approximately 38% longer when divers wore the prototype aerogel garment under a TLS350 dry suit than when they wore an M400 Thinsulate liner.
2. The prototype aerogel garment enhanced thermal protection to the fingers and toes, although thermal stress to these body regions was the most frequent reason for aborting dives.
3. Dive durations were predominately dictated by cold hands and feet. Future research should include work on localized active heating of the hands and feet to augment the thermal insulation of the prototype aerogel garment.
4. Two diver-subjects reported that the prototype aerogel garment was less flexible than the Thinsulate liner. Future development should create a more flexible aerogel material with better sizing of the garment pattern to allow an improved fit.



## REFERENCES

1. Commander, Naval Sea Systems Command, *Task Assignment 04-16: Manned Evaluation of a Composite Cold Water Diving Garment Using Liquids and Superinsulation Aerogel Materials*, 31 Aug 2004.
2. Southwest Research Institute, *Development of a Composite Cold Water Diving Garment Using Liquids and Super-Insulation Aerogel Materials*, published under Office of Naval Research Contract No. N00014-04-C-0044, Office of Naval Research, Arlington, VA.
3. A. S. Jackson and M. L. Pollock, "Generalized Equations for Predicting Body Density in Men," *Brit. J. Nutrition*, Vol. 40 (1978), pp. 497-504.
4. W. E. Siri, "Gross Composition of the Body," in J. H. Lawrence and C. A. Tobias, eds., *Advances in Biological and Medical Physics, IV* (New York: Academic Press, 1956), pp. 239 - 280.
5. J. C. Chao, M. L. Nuckols, and W. S. Meyer, *Proof of Concept: Manned Evaluation of a Composite Cold Water Diving Garment Using Liquids and Super-Insulation Aerogel Materials*, NEDU Protocol 04-44/32160, Navy Experimental Diving Unit, Jan 2005.
6. N. L. Ramanathan, "A New Weighting System for Mean Surface Temperature of the Human Body," *Journal of Applied Physiology*, Vol. 19 (1964), p. 5313.

# **APPENDIX A** **IN-WATER DIVER THERMAL ASSESSMENT QUESTIONNAIRE**

Test Date (DD/MMM/YY) \_\_\_\_\_

Time (HR:MIN) \_\_\_\_\_

Diver's Name (Last, First, M.I.) \_\_\_\_\_

1. ARE YOU COMFORTABLE?

1      2      3      4      5      6      7      8      9      10

Very Uncomfortable

Most Comfortable

2. ARE YOU WET?

1      2      3      4      5      6      7      8      9      10

Completely Dry

Completely Wet

3. ARE YOU COLD OR HOT?

1      2      3      4      5      6      7      8      9      10

Very Cold

Perfect

Very Hot

4. ARE YOUR HANDS COLD OR HOT?

1      2      3      4      5      6      7      8      9      10

Very Cold

Perfect

Very Hot

5. ARE YOUR FEET COLD OR HOT?

1      2      3      4      5      6      7      8      9      10

Very Cold

Perfect

Very Hot

6. ARE YOU SHIVERING?

1      2      3      4      5      6      7      8      9      10

Absent

Most Shivering

7. IS THE LINER COMFORTABLE?

1      2      3      4      5      6      7      8      9      10

Least

Most Comfortable

8. DO YOU WISH TO QUIT SOON?

☐ YES

☐ NO

# APPENDIX B IN-WATER DIVER THERMAL ASSESSMENT QUESTIONNAIRE DATA

Aerogel	Dive Interval (minutes)																							
	30								60								90							
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
1	3	1	4	4	3	1	8	no	6	1	4	4	3		8	no	6	1	3	3	2	2	8	no
2	7	1	7	6	6	1	7	no	5	3	5	3	3	3	7	no	dive aborted							
3	8	2	4	4	4	1	8	no	6	2	4	3	3	1	7	no	6	3	2	2	2	1	6	no
4	8	1	5	5	4	1	5	no	7	1	4	4	3	1	7	no	6	1	3	3	3	1	5	no
5	8	1	5	5	5	1	8	no	8	1	5	5	5	1	8	no	6	3	4	4	4	1	5	no
6	8	1	5	5	3	1	7	no	7	1	5	5	4	1	7	no	6	1	4	3	3	1	7	no
Mean	7.0	1.2	5.0	4.8	4.2	1.0	7.2		6.5	1.5	4.5	4.0	3.5	1.4	7.3									
Std Dev	0.5	0.4	1.0	0.6	1.0	0.0	1.1		1.0	0.8	0.5	0.9	0.8	0.8	0.4									

Thinsulate	Dive Interval (minutes)																							
	30								60								90							
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
1	8	1	4	4	4	1	8	no	7	1	4	3	3	1	7	no	7	1	3	2	2	1	7	no
2	7	1	4	3	3	1	8	no	7	1	4	3	3	1	7	no	dive aborted							
3	8	1	4	4	4	1	9	no	7	1	3	2	2	1	8	no	6	1	2	2	2	3	8	no
4	8	1	4	4	4	1	8	no	5	6	3	2	2	1	8	no	3	5	1	1	1	3	8	no
5	5	3	5	4	3	9	8	no	8	2	5	5	5	1	9	no	6	2	4	4	4	1	9	no
6	8	1	5	4	4	1	8	no	6	1	4	3	3	1	7	no	dive aborted							
Mean	7.3	1.3	4.3	3.8	3.7	2.3	8.2		6.7	2.0	3.8	3.0	3.0	1.0	7.7									
Std Dev	1.2	0.8	0.5	0.4	0.5	3.2	0.4		1.0	1.9	0.7	1.1	1.1	0.0	0.8									

Notes: Question numbers are indicated by Q#, per Appendix A. Mean scores and respective standard deviations calculated for each question with a numerical response up to the 60-minute interval.

**APPENDIX C**  
**POSTDIVE QUESTIONNAIRE**

- (1) How well did the liner fit? Please elaborate on any specific areas where the liner was too loose or tight, or where the fabric creased under your wet suit.
  
- (2) Comment on your ability to move about and maneuver while wearing this liner? Easy? Difficult? Please elaborate on any specific maneuvers that were particularly difficult.
  
- (3) How would you feel about using the system during a long (e.g., combat) swim? Please elaborate on how the system might interfere with a long swim.
  
- (4) How well could you move your hands and manipulate objects while wearing the glove liners under wet suit gloves? Please elaborate on any specific activities that you found particularly difficult.
  
- (5) What is your overall impression of this liner's ability to provide you with extra heat?
  
- (6) Any suggestions for changing / improving the liner?